QuaRRi: a new methodology for rock-fall risk analysis and management in quarry exploitation

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MATTEO FALANESCA *, LUCA BORIO*, ANDREA PICCHIO**, DANIELE PEILA***

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Introduction

Among the various geological hazards, rock-fall phenomena represent one of most frequent causes of accidents in quarries, as clearly shown in many databases throughout the world (Girard 2008; Peila et al. 2011; Falanesca, Borio 2010).

Several procedures can be found in technical literature which can be used to classify and evaluate risk to infrastructures located near unstable rock slopes (Pierson et al. 1990; Hudson 1992; Franklin, Senior 1997; Budetta 2004; Hoek 2007, Peila and Guardini 2008).

However, for a complete definition of rockfall risk assessment in an open pit, it is not possible to simply transfer and apply the risk assessment procedures that have been developed for civil infrastructures, since detachments can occur from both natural slopes overhanging the exploited rock mass and from artificially created slopes (benches and berms), the quarry activities can trigger detachments and finally the geometry of quarry faces change continuously as do the rock mass properties. Moreover, the fact that workers often carry out activities on both benches and berms and in quarry yards under the slope faces, even for long periods, is a critical aspect that should be considered. It is therefore necessary to use methods that are able to take a "dynamic" quarry design into account, as suggested in the Prevention through Design approach (Bealko et al. 2008; Bersano et al. 2009, 2010; Sattarvand, Neiman-Delius 2008) in order to obtain good results, in terms of the health and safety of workers (Jurdziak, Kawalec 2007).

* Research Associate, ** Ph.D. student, *** Associate Professor, Department of Land, Environment and Geoengineering; Politecnico di Torino, Italy.

Alejano et al. (2008) have developed a methodological approach to estimate potential rockfall risks in quarry activities, which has been tested on Spanish case histories. This procedure, named "Rockfall Risk Assessment for Quarries", even though very simple and feasible, does not take the full variability of a rockfall phenomena into due account, and in particular does not permit the positive effect of the installation of rock fall protection devices, such as drapery nets or net fences, which are now starting to be widely used in mine activities (Peila et al. 2006), to be evaluated.

1. Risk assessment

As already discussed by Peila et. al. (2011), risk [R] is defined as the combination of the likelihood of the occurrence of a hazardous event and the ill health that can be caused by the event itself (OHSAS 18001 – British Standard Institute 2007). It is usually expressed by the following formula:

$$[R] = [M] \times [FA] \tag{1}$$

where [M] is the magnitude of the event, evaluated in terms of economic loss or, in the case of events involving workers, in terms of lost days (Faina et al. 1996; Campus et al. 2007) and [FA] is the yearly expected frequency of occurrence of the event (an accident due to rockfalls in the present study) expressed as events/year.

The well known formula (1) is generally valid both for researches that deal with the health and safety for workers and researches that deal with geological risks.

If the risk is expressed as the probability of damage to workers [PD], the following formula can be used:

$$[R] = [PD] \times [FA] \tag{2}$$

$$[PD] = [ED] \times [FC] \times [N] \tag{3}$$

where: [ED] is the harm evaluated in terms of lost work days; [FC] is the exposure factor, which depends on the percentage of work time during which the workers are exposed to potentially hazardous conditions and [N] is the number of workers potentially subject to the harm.

Using these formulas, it is possible to numerically quantify the risk of a work activity on a job site. This procedure requires that the various parameters should not be affected by personal evaluations, but should be defined according to objective and feasible evaluations. However, the numerical quantification of the various parameters (i.e. [FA], [ED], [FC]) is not easy, particularly, in the studied case, and the procedure for this quantification cannot be defined in a unique manner.

It is clear that the influence of the measured data on the [FA] value is influenced to a great extent by the representativeness of the input data and by their deviation from the average values in each working context. As a result of the evaluation procedure, the weight of each input data should be known and appropriate quantification tools should be used. Furthermore, the limits in the quantification of the parameters should be known and techniques that are able to minimize deviations should be used. The approach that has been used in this research (Faina et al. 1996) to evaluate [FA] is a predictive analysis that is based on the application of hazard evaluation techniques.

This methodology can be applied since a rockfall event depends on some "geo" parameters that have already been studied and their influence on rockfall events has partly been quantified in technical literature. However, it should be recalled that, in the case of an open pit mines and quarries, the following key points should be considered:

— it is difficult, if not impossible, to define the "geo" parameters in a unique way for the whole quarry face since they can vary to a great extent from one portion of the slope to another (Sattarvand, Niemamm-Delius 2008). Furthermore, the quarry face moves continuously inside the rock mass. The confidence limits of the parameters can only be defined using a statistical analysis or using weights that are defined on the basis of the experience of a large number of examples and case histories, which are usually not available;
— most of the data are obtained on the basis of a surface survey or on a usually limited number of core samplings or punctual surveyings. Rock mass characterization is extrapolated underground on the basis of designer experience, the use of some empirical rules, such as rock mass classifications, or using geostatistical methods.

In the present work, the evaluation has mainly been conducted on the basis of engineering judgement and experience gained from similar cases presented in technical literature (Alejano et al. 2007, 2008).

Finally, in order to obtain a correct risk assessment, it is important to correctly define the harm. This parameter mainly depends on the technical choices that have been made in the quarry, such as adequate protection, human factors, information and formation of the workers and exposure factors (Faina et al. 1996).

For the proposed methodology, this definition requires a complete evaluation of the quarry work conditions (position of the workers during the working cycle, type of machines, etc.), of the slope, of the yard positions during time.

2. Proposed methodology for rockfall risk assessment

For the above-mentioned reasons, a new risk assessment approach, named "Quarry Rockfall Risk" (QuaRRi ver. 1.0), which is based on the analysis of the falling trajectories

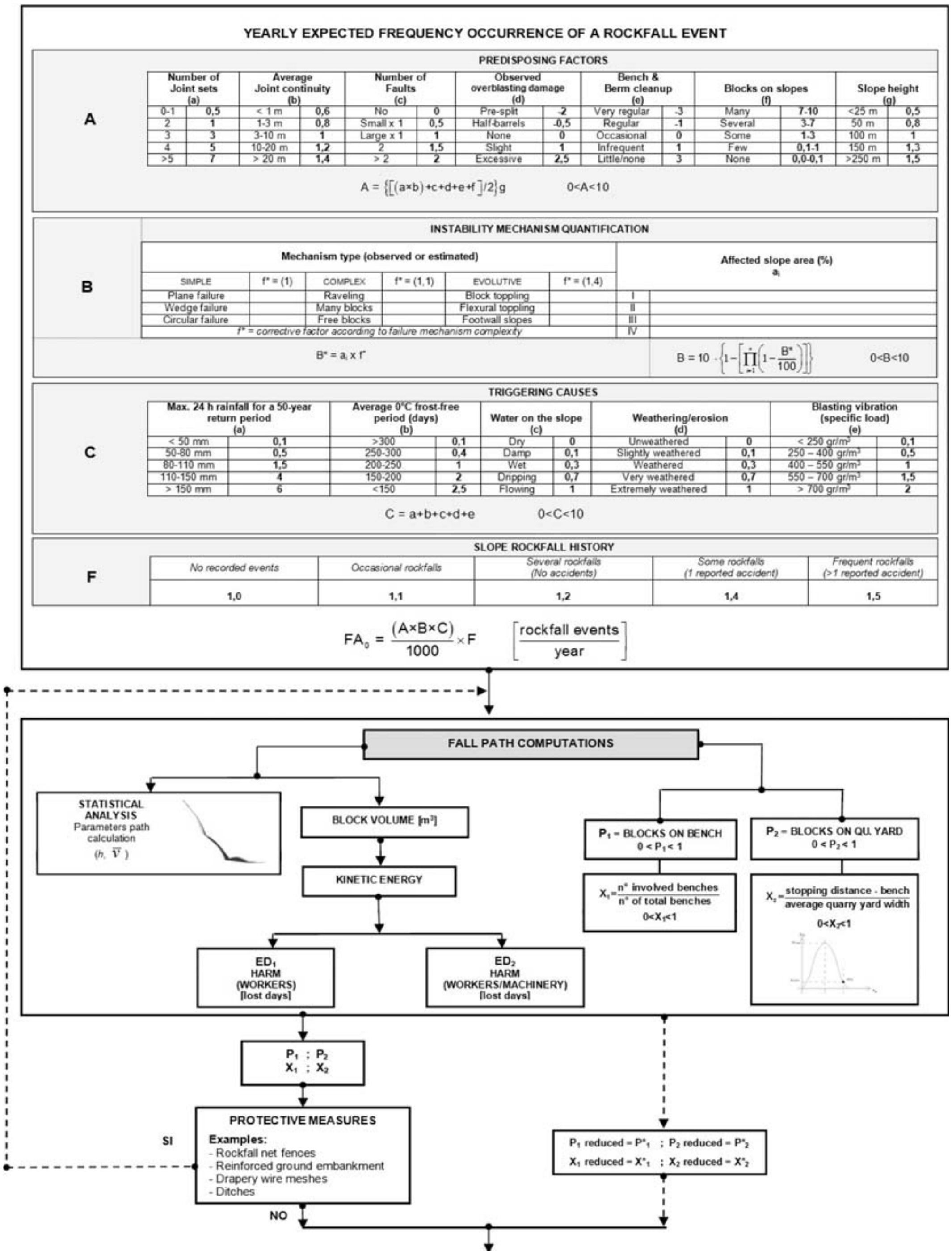

Fig. 1A. Logical scheme and computational development of the QuaRRi method (Peila et al. 2011) (Part 1)

Rys. 1A. Schemat logiczny i komputerowa prezentacja metody QuRRi (Peoila et al. 2011) (część 1) and, which is able to take into account the influence of protective measures, has been developed.

The procedure that takes into account the various parameters which are involved in rockfall phenomena (Peila et al. 2006) and, by defining their weight, gives the data that has to be introduced into the risk matrix, is based on the following main steps (Peila et al. 2011), which are summarized in Figs. 1A and 1B:

— evaluation of the rock-fall prone condition of the slope. The geological and geotechnical parameters and the environmental parameters (quarry activities and local weather conditions) are weighted to calculate the probability a rock movement occurring. This step is based on the approach that has been proposed and tested by Alejano et al. (2008). The geological and geotechnical parameters and the environmental parameters, that is the weather conditions and quarry activities (Softic et al. 2008), are weighed to calculate the probability of a rock movement occurring;
— computation of the block trajectories, using a statistical approach of the block energy;
— evaluation of the probability of interference between the falling block and the workers, taking into account the time the workers spend in an area at risk;

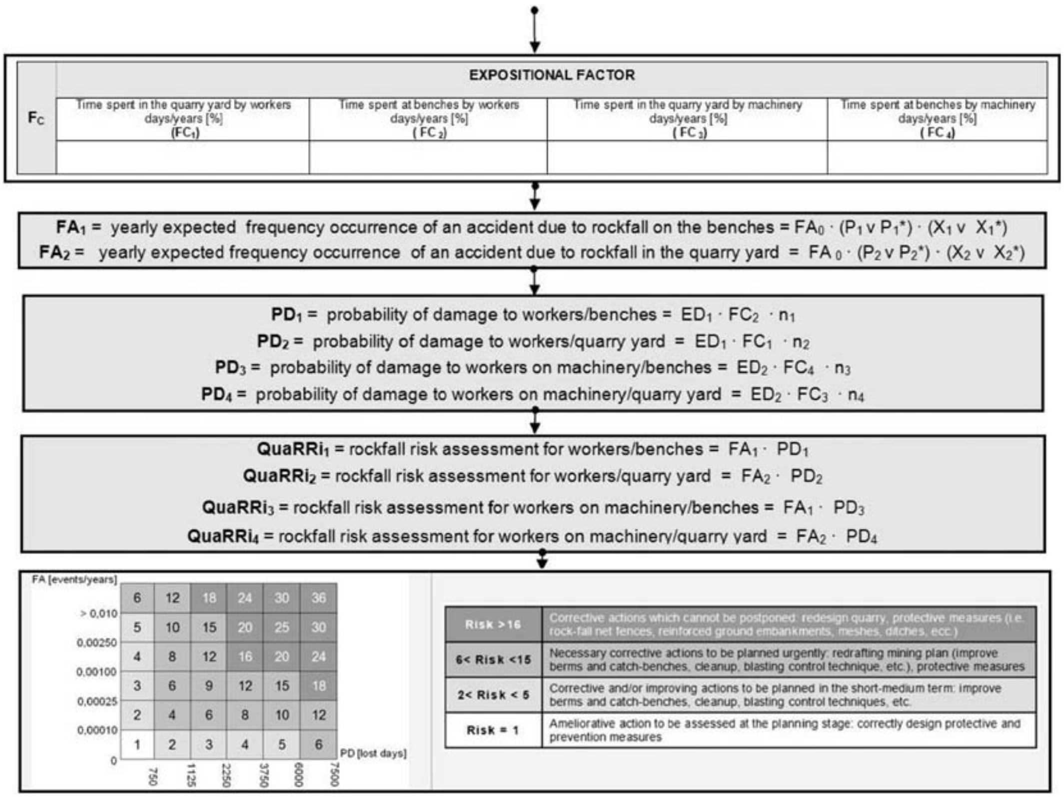

Fig. 1B. Logical scheme and computational development of the QuaRRi method (Peila et al. 2011) (Part 2)

Rys. 1B. Schemat logiczny i komputerowa prezentacja metody QuRRi (Peolia et al. 2011) (część 2)

— evaluation of the risk using a risk matrix approach. Four different conditions have been defined: these range from a dark area, where the immediate setting up of corrective actions is necessary, to a light area, where some corrective or improving actions could be planned and installed in the short term;
— definition of the need for prevention interventions (constraints on access to certain quarry areas, control of local detachments from the slopes, slope cleanups, etc.) and/or of protective devices, such as net fences and drapery meshes, and assessment of the risk reduction that can be obtained.

The proposed methodology can be considered a valuable tool for quarry managers since it can be used to evaluate newly exposed rock faces, thus allowing decision makers to evaluate the risk conditions that must be faced in a continuous "dynamic" process like quarrying and, if necessary, the need for protection devices.

3. Case studies

The proposed methodology has been applied to two case histories that were affected by rock-fall events: an ornamental stone quarry located in the Firenzuola district (Italy) and in a limestone quarry located in the Lucca district (Italy).

The results are presented and discussed hereafter.

3.1. QuaRRi calculation for an ornamental stone quarry

The quarry (Fig. 2) is mined using the dynamic splitting method (Coli et al., 2007). Two drilling machines work simultaneously in different parts of the quarry yard and the resulting blocks are hauled by front-head loaders on dumpers (Fig. 3). In order to reduce rockfall risks, the quarry manager has installed rockfall net fences in correspondence to the berms that have been abandoned, each 15 m on the face. The QuaRRi method has been applied to a sector of the slope, which has been identified as one of the most hazardous. An analysis was performed without protective measures in order to verify the need of the installation of protection devices such as rockfall net fences. The obtained risk values (Fig. 4) have shown that a continuous control of the slope stability is necessary in the quarry with cleaning up of the unstable local blocks and local stabilization and prevention measures, such as drapery net meshes. Alternatively, it would be possible to install some net fences that would be able to intercept the block trajectories and stop the blocks.

3.2. QuaRRi calculation for a limestone quarry

The quarry (Peila et al. 2011) is mined with individual benches using explosives and the blasted muck is hauled, by two front head loaders on two dumpers, to a quarry yard above

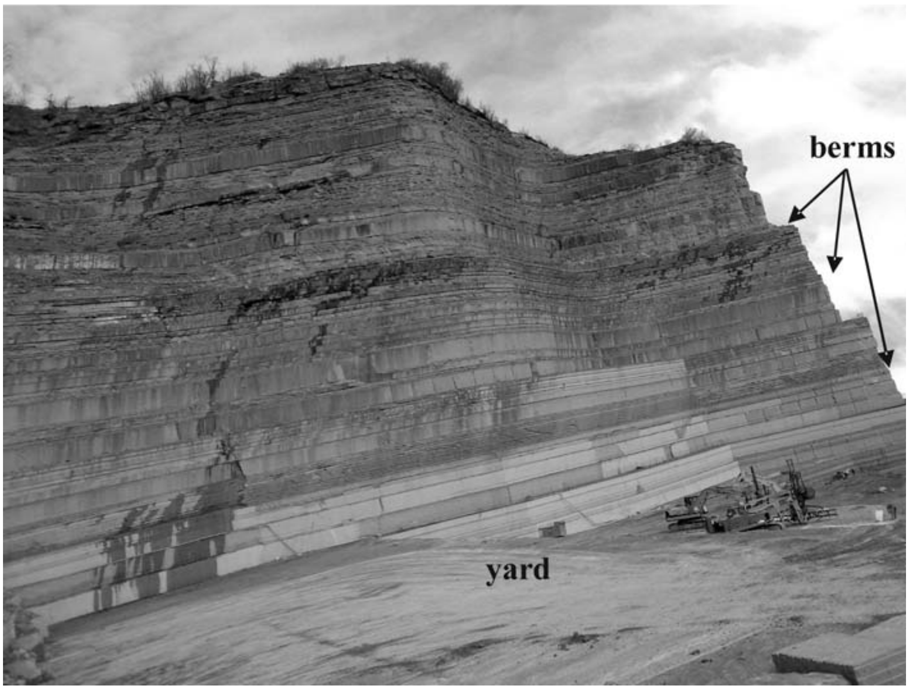

Fig. 2. Overall view of the ornamental stone quarry

Rys. 2. Ogólny widok kopalni kamienia dekoracyjnego

Fig. 3. View of the machines on the quarry yard exposed to rock-fall phenomena

Rys. 3. Stojące na zapleczu kamieniołomu maszyny uszkodzone przez odłamki skał

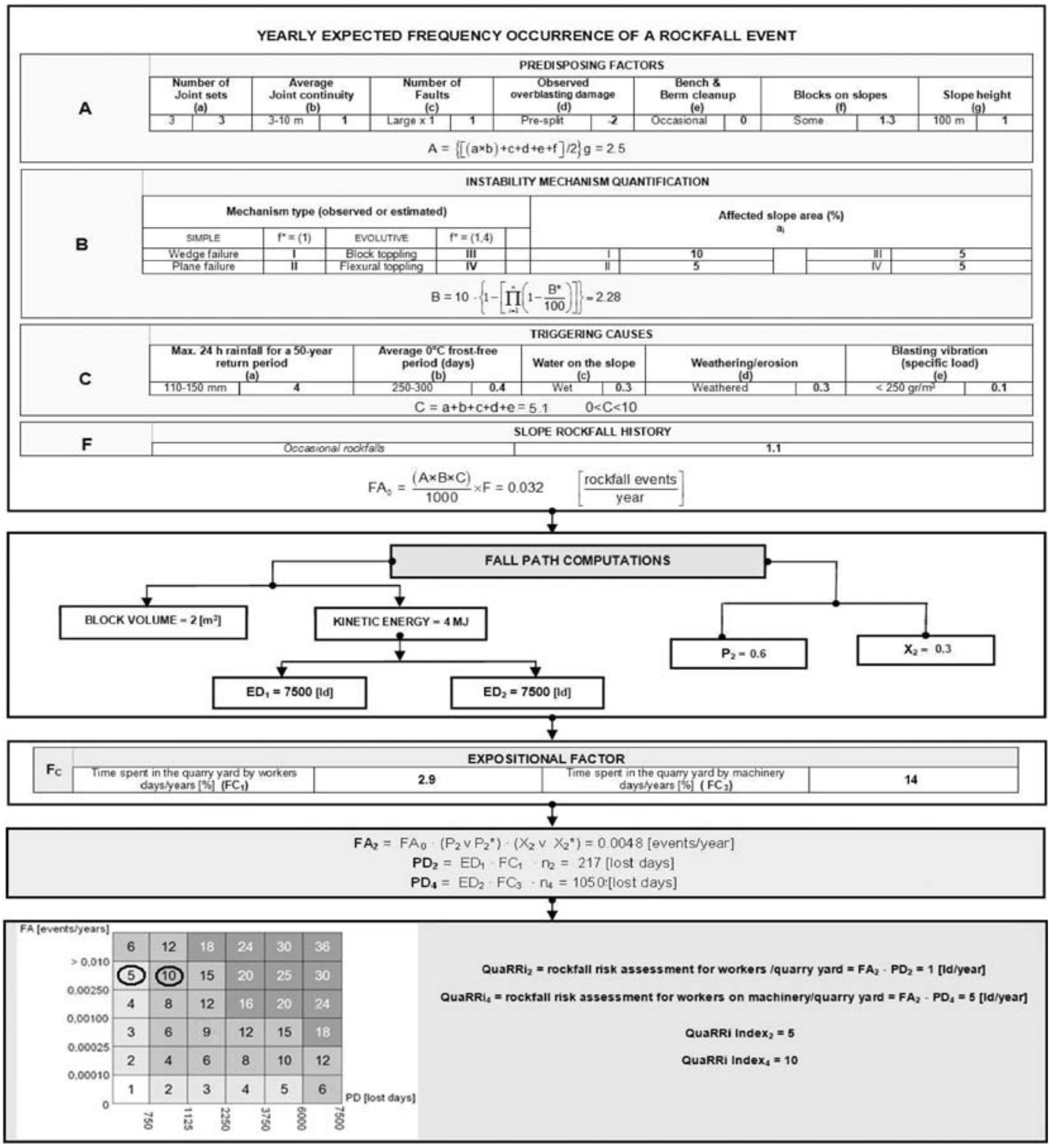

Fig. 4. QuaRRi datasheet for an ornamental quarry in the Firenzuola district (Italy)

Rys. 4. Zestawienie danych QuaRRi dla kopalni kamienia dekoracyjnego w okręgu Firenzuola (Włochy)

(Fig. 5); these dumpers discharge the muck through a shaft to the quarry yard to reach the the main crushers.

In order to reduce rockfall risks, in correspondence to the upper quarry yards, and, in particular in correspondence to the access roads that lead to the mine shaft, the quarry manager has recently installed a number of safety measures including drapery wire meshes on the rock faces (Fig. 6).

Fig. 5. Overall view of the limestone quarry

Rys. 5. Widok ogólny kopalni wapnia

The QuaRRi method has been applied to verify the specific local conditions of this portion of the quarry. The results (Fig. 7) have confirmed the assessment of the quarry manager since the QuaRRi index has clearly shown the need for the installation of protection devices on the rock slopes in order to render it safe. After the installation of these device, the QuaRRi index was reduced to 1, thus showing a correct approach toward risk reduction.

Fig. 6. Details of the drapery wire meshes and net fences installed on the rock slopes to protect the quarry yard

Rys. 6. Szczegółowy widok stalowych sieci i płotów siatkowych zainstalowanych na zboczach skał zabezpieczających teren kamieniołomu

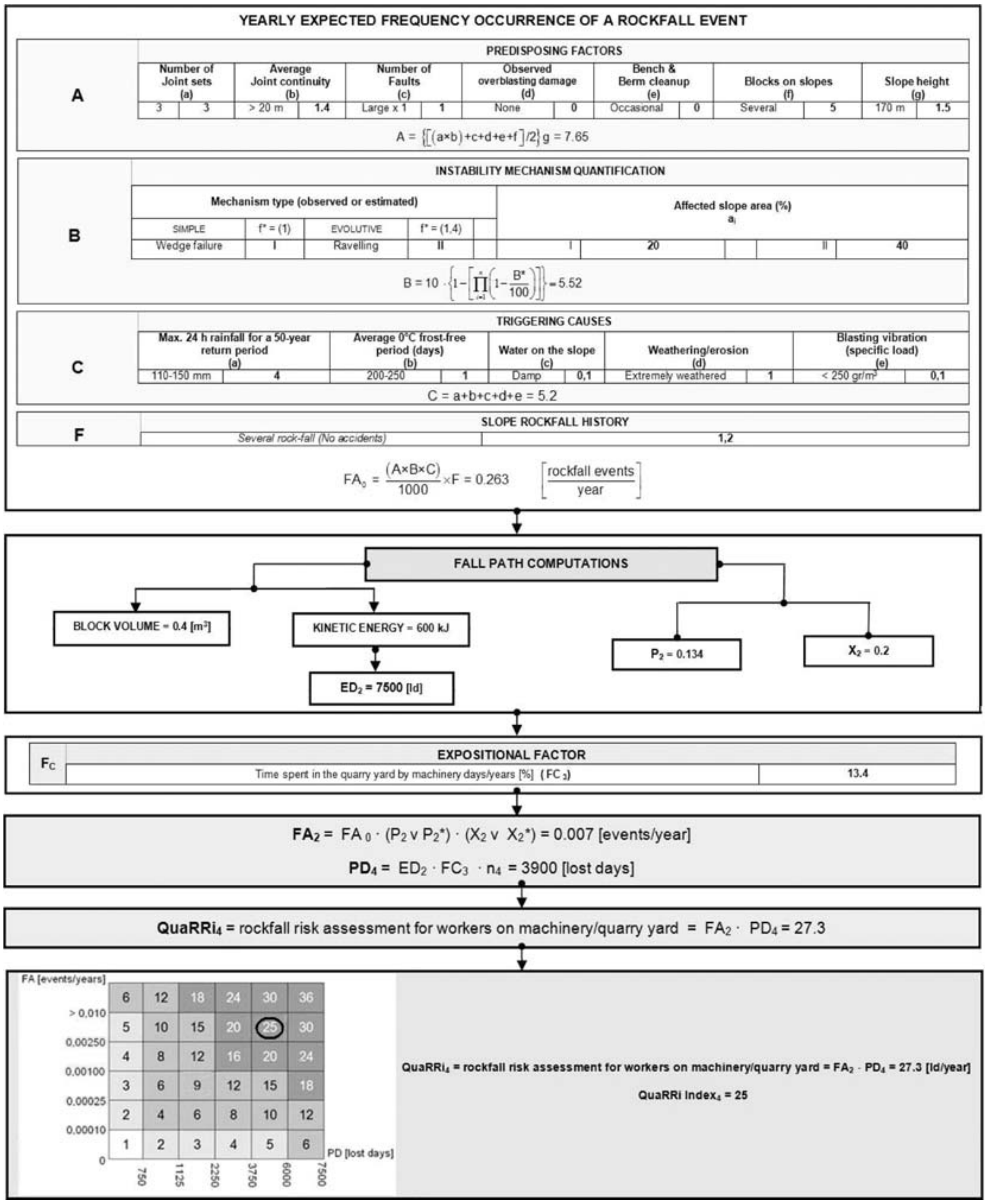

Fig. 7. QuaRRi datasheet for a limestone quarry in the Lucca district (Italy)

Rys. 7. Zestawienie danych systemu QuaRRi dla kopalni wapnia w okręgu Lucca (Włochy)

Conclusions

On the basis of an analysis of international accident databases, it is possible to highlight that rockfalls in quarries are the most dangerous events for workers of all the various types of geological instabilities. A methodology which permits the various rock fall prone parameters that can trigger detachment to be weighed together with a statistical evaluation of the falling trajectories and the workers' exposure factor, which was developed according to the philosophy of the *Prevention through Design*, has been proposed as a tool to provide the risk conditions of a quarry slope (QuaRRi methodology). The most complex aspect of the proposed method is the definition of the geological parameters and their weight, which are used to provide the evaluation of the yearly expected frequency of the event. The proposed evaluation approach can easily be adopted to different values of the parameters, which can be changed if different environmental conditions are encountered in the quarry areas.

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QuaRRI – NOWA METODOLOGIA ANALIZY RYZYKA OBRYWANIA SIĘ SKAŁ I JEGO ZARZĄDZANIA W KAMIENIOŁOMACH

Słowa kluczowe

Kopalnie odkrywkowe kamienia, Zapobieganie poprzez Projektowanie (PtD), odrywanie się skał, ocena ryzyka, zdrowie i bezpieczeństwo pracownika

Streszczenie

Obrywanie się skał jest jednym z najbardziej niebezpiecznych zjawisk geologicznych zachodzących przy wydobywaniu kamienia. Obecnie zarządzający i projektanci dysponują szeregiem środków, które pomagają precyzyjnie określić stopień ryzyka, jednocześnie podnosząc bezpieczeństwo pracy zarówno kamieniarzy/pracowników bezpośrednio wydobywających kamień jak i kadry kierowniczej. Środki te mają przede wszystkim funkcję prewencyjną. Dlatego też sprawą pierwszej wagi jest określenie różnorodnych parametrów specyficznych dla danych warunków oraz precyzyjne zdefiniowanie, które z nich są najbardziej istotne w przypadku obrywania się skał poprzez stosowanie metody Zapobieganie poprzez Projektowanie (*Prevention through Design* – PtD).

Zaprezentowany tutaj system oceny ryzyka, na którym mogą się oprzeć decydenci w najbardziej krytycznej fazie oszacowania niebezpieczeństwa przy oderwaniu się skały, oferuje również aktualne informacje niezbędne do prowadzenia prac przy eksploatacji kamieniołomów przy równoczesnym zminimalizowaniu ryzyka.

QuaRRI: A NEW METHODOLOGY FOR ROCK-FALL RISK ANALYSIS AND MANAGEMENT IN QUARRY EXPLOITATION

Key words

Open pit mine, Prevention through Design, rock-fall, risk assessment, workerr' health and safety

Abstract

Rockfall is one of the most critical geological events that can affect quarrying activities. Nevertheless, few tools are currently available to help designers and managers correctly define the risk conditions and quantify the advantages, in terms of workers' safety and quarry management, that can be obtained using suitable prevention devices. For this reason it is necessary to evaluate the various parameters that are involved, and to define the most important and which have the greatest influence on rock-fall phenomena, taking into account the Prevention through Design approach.

A risk evaluation system which is able to support decision makers in the critical rockfall risk assessment phase, and offer decision makers the updated information that is necessary for a continuous and dynamic operation design during exploitation activities is here presented and discussed.